

Heavy Flavor Physics in PHENIX

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Abstract. Heavy quarks are good probes of the hot and dense medium created in relativistic heavy ion collisions since they are mainly generated early in the collision and interact with the medium in all collision stages. In addition, heavy flavor quarkonia production is thought to be uniquely sensitive to the deconfined medium of the Quark Gluon Plasma (QGP) through color screening. Heavy quark production has been studied by the PHENIX experiment at RHIC via measurements of single leptons from semi-leptonic decays, in both the electron channel at mid-rapidity and in the muon channel at forward rapidity. Large suppression and azimuthal anisotropy of single electrons have been observed in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. These results suggest a large energy loss and strong flow of the heavy quarks in the hot, dense matter. The PHENIX experiment has also measured J/ψ production in $p+p$, d+Au, Cu+Cu, and Au+Au collisions at energies up to $\sqrt{s_{NN}} = 200$ GeV. In central Au+Au at 200 GeV, more suppression is observed at forward rapidity than at central rapidity. This can be interpreted either as a sign of quark recombination, or as a hint of additional cold nuclear matter effects. Selected PHENIX results on open heavy flavor and heavy quarkonia production in $p+p$, d+Au, Cu+Cu, and Au+Au collisions are presented. The status of the recent PHENIX upgrade of the central Silicon Vertex Tracker (VTX) and its performance are elucidated.

1. Introduction

The measurement of inclusive hadron yields in central Au+Au collisions at RHIC led to the discovery of the suppression of hadron production at large transverse momenta (p_T) compared to $p+p$ collisions [1]. This is generally attributed to the energy loss of light partons in the dense nuclear matter created at RHIC. Heavy quarks, i.e. charm and beauty, are believed to be mostly created in initial hard scattering processes of partons [2] and thus are excellent probes of the hot and dense matter formed in nucleus–nucleus collisions at high energy. While some of the produced pairs form bound quarkonia, the vast majority hadronize into hadrons carrying open heavy flavor. They interact with the medium and are expected to be sensitive to its energy density through the mechanism of parton energy loss. Due to the large mass of heavy quarks the suppression of small angle gluon radiation should reduce their energy loss, and consequently any suppression of heavy-quark mesons like D and B mesons at high p_T is expected to be smaller than that observed for hadrons consisting of light quarks [3].

Heavy quark production has been studied by the PHENIX experiment at RHIC via measurements of single leptons from semi-leptonic decays in both the electron channel at mid-rapidity and in the muon channel at forward rapidity. In this paper I will summarize the latest PHENIX results concerning open and closed heavy flavor production as a function of beam energy and systems size, and will give an overview of the latest progress with the Silicon Vertex Tracker (VTX).

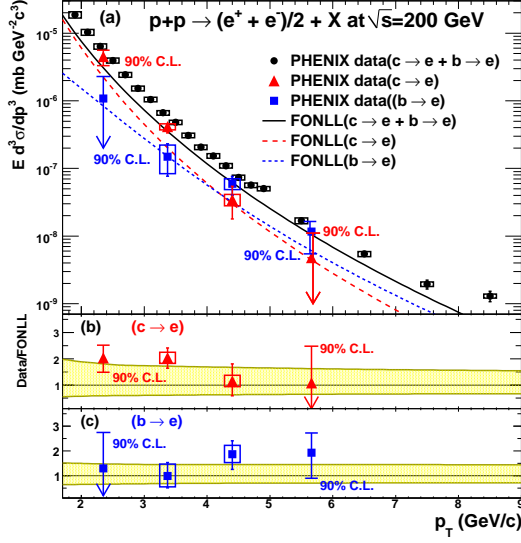


Figure 1. Invariant cross-sections of electrons from charm and bottom with the FONLL calculation in $p + p$ collisions at $\sqrt{s_{NN}} = 200$ GeV. Panels (b) and (c) show the ratios of data points over the FONLL prediction as a function of electron p_T for charm and bottom, respectively. The shaded area shows the uncertainty in the FONLL prediction [5, 6].

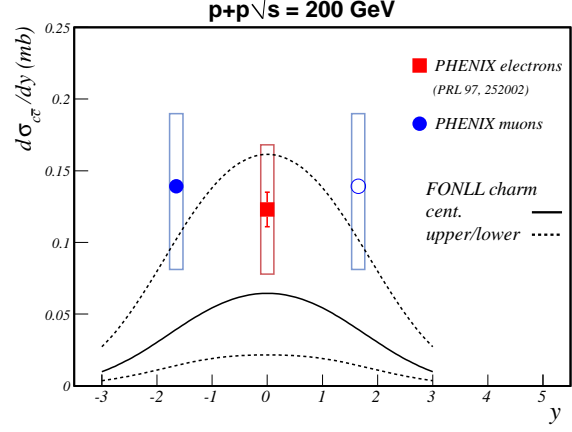


Figure 2. Heavy flavor, $(c\bar{c})$, production cross-section as a function of rapidity in $p + p$ collisions at $\sqrt{s_{NN}} = 200$ GeV, measured using semi-leptonic decay to electrons (closed square) and to muons (closed circles) [7].

2. PHENIX Experiment

The PHENIX detector [4] comprises three separate spectrometers in three pseudorapidity (η) ranges. Two central arms at midrapidity cover $|\eta| < 0.35$ and have an azimuthal coverage (ϕ) of $\pi/2$ rad each, while muon arms at backward and forward rapidity cover $-2.2 < \eta < -1.2$ and $1.2 < \eta < 2.4$, respectively, with full azimuthal coverage. In the central arms, heavy quark production was studied via measurements of single leptons (electrons) from semi-leptonic decays. Charged particle tracks are reconstructed using the drift chamber and pad chambers. Electron candidates are selected by matching charged tracks to hits in the Ring Imaging Cherenkov (RICH) counters and clusters in the Electromagnetic Calorimeter (EMCal). At forward and backward rapidity, the heavy quark production is measured via dimuon decays. Muons are identified by matching tracks measured in cathode-strip chambers, referred to as the muon tracker (MuTr), to hits in alternating planes of Iarocci tubes and steel absorbers, referred to as the muon identifier (MuID). Each muon arm is located behind a thick copper and iron absorber that is meant to stop most hadrons produced during the collisions, so that the detected muons must penetrate 8 to 11 hadronic interaction lengths of material in total. Beam interactions are selected with a minimum-bias (MB) trigger requiring at least one hit in each of the two beam-beam counters (BBCs) located at positive and negative pseudorapidity $3 < |\eta| < 3.9$.

3. Open heavy flavor

Open heavy flavor production is measured in PHENIX through the measurement of inclusive electrons or muons. For the electron measurement, the electrons that come from either meson decay or photon conversions are measured and subtracted from the inclusive spectrum and the remainder is attributed to electrons coming from the semi-leptonic decay of D and B mesons. This remainder is also referred to as the non-photonic electron component. PHENIX

has measured spectra of the single electrons [5, 6] and single muons [19] from heavy flavor in $p+p$ collisions at 200 GeV as well single electrons from heavy flavor in Au+Au [9, 10], Cu+Cu [7, 11] and d+Au [12] collisions. Figure 1(a) shows the measured single electron spectra from charm (triangles) and bottom (squares) compared to the FONLL predictions [6, 13]. The measured spectrum of single electrons (circles) is also shown for reference. The single electron from charm and bottom are measured from the ratio, $(b \rightarrow e)/(c \rightarrow e + b \rightarrow e)$, and the spectrum of the electrons are from heavy flavor decays. Panel (b) ((c)) shows the ratio of the measured charm (bottom) cross-sections to the FONLL calculation for charm production. The shaded area shows the uncertainty in the FONLL prediction. The larger mass makes this uncertainty smaller in the case of bottom quarks. These calculations agree with the data for bottom production. The same is true for charm within the theoretical uncertainty.

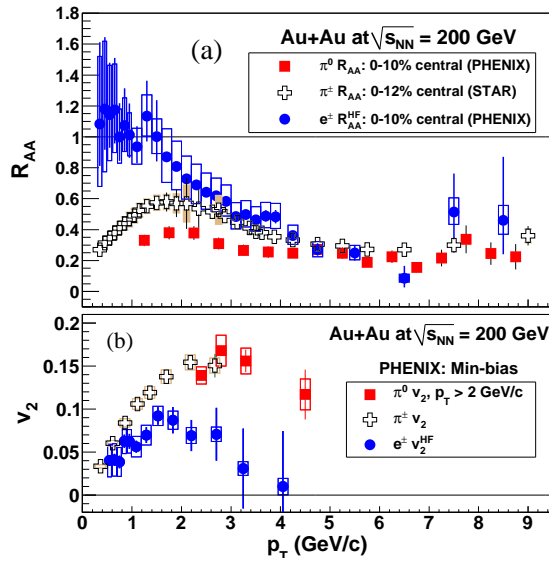


Figure 3. Nuclear modification factor, R_{AA}^{HF} , for HF electrons compared with the R_{AA} of π^0 in central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV, see panel (a). Panel (b) considers the anisotropic flow of HF electrons v_2^{HF} with that of v_2 of π^0 and π^\pm in minimum-bias Au+Au collisions [9, 10].

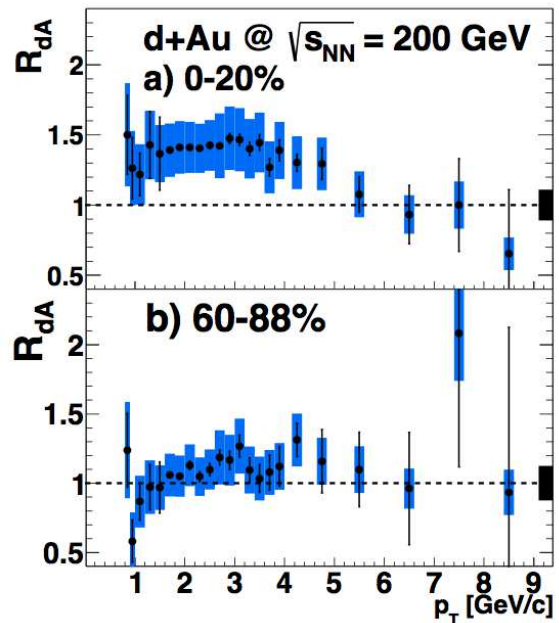


Figure 4. Nuclear modification factor, R_{dAu}^{HF} , for HF electrons measured in d+Au collisions at $\sqrt{s_{NN}} = 200$ GeV for a) the most central collisions and for b) the most peripheral collisions [12].

Heavy-flavor spectra in $p + p$ collisions, are measured via single leptons from semi-leptonic decays in both the electron channel at mid-rapidity and in the muon channel at forward rapidity as a function of p_T . These spectra are used to estimate the charm differential production cross-section, $d\sigma_{c\bar{c}}/dy$ [7]. Estimation of the full charm cross-section requires a theoretical calculation in order to extrapolate the measurement down to $p_T = 0$ GeV/c. A set of fixed-order-plus-next-to-leading-log (FONLL) calculations as shown on Fig. 1 have been used [7]. Additionally, the contribution of bottom quark decay to the heavy flavor electron (muon) p_T distribution becomes increasingly relevant for $p_T > 4$ GeV/c, but has a negligible contribution to the integral and is ignored hereafter. Using this method, the integrated charm production cross-section at mid- and forward-rapidity are shown in Fig 2.

In heavy ion collisions, the RHIC experiments have revealed a suppression of the high transverse momentum component of hadron spectra at mid-rapidity in central Au+Au collisions compared to scaled momentum spectra from $p+p$ collisions at the same energy, $\sqrt{s_{NN}} = 200$ GeV as shown in Fig. 3a. This effect, originally proposed by Bjorken, Gyulassy, and others [14]

rests on the expectation of a large energy loss of high momentum partons scattered in the initial stages of collisions in a medium with a high density of free color charges. According to QCD theory, colored objects may lose energy by the bremsstrahlung radiation of gluons [15]. Such a mechanism would strongly degrade the energy of leading partons, reflected in the reduced transverse momentum of leading particles in the jets emerging after fragmentation into hadrons. Adding to this discovery of suppression of particles at high transverse momentum, two very striking results have been seen for open heavy flavor from the PHENIX experiment via the measurement of electrons from semi-leptonic decays of hadrons carrying charm or bottom quarks. First, heavy mesons, despite their large mass, exhibit a suppression at high transverse momentum compared to that expected from $p + p$ interactions. This suppression is found to be similar to that of light mesons, which implies a substantial energy loss of fast heavy quarks while traversing the medium, see Fig. 3a; this shows the nuclear modification factors measured for different types of particle in Au+Au collisions at 200 GeV. The nuclear modification factor is defined as:

$$R_{AA}(p_T) = \frac{\text{yield per A + A collisions}}{N_{\text{bin}} \times (\text{yield per p + p collisions})} \\ = \frac{d^2N^{A+A}/dp_T d\eta}{N_{\text{bin}} d^2N^{p+p}/dp_T d\eta}$$

It involves scaling measured distributions of nucleon-nucleon transverse momentum by the number of expected incoherent binary collisions, N_{bin} [16]. Secondly, an elliptic flow is observed for heavy mesons which is comparable to that of light mesons like pions, see Fig. 3b. This implies that the heavy quarks are in fact sensitive to the pressure gradients driving hydrodynamic flow giving new insights into the strongly coupled nature of the QGP fluid at these temperatures.

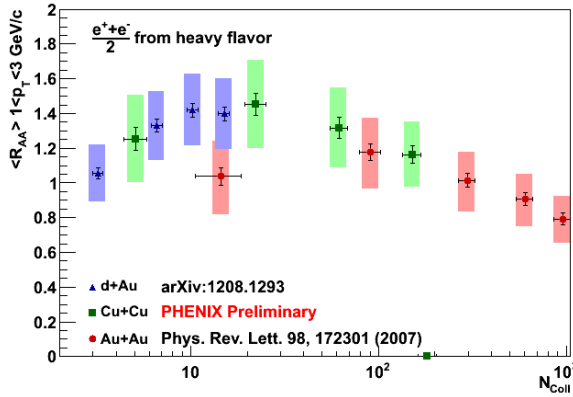


Figure 5. Nuclear modification factor for HF electrons for Cu+Cu collisions compared with those for d+Au and Au+Au. The $R_{A(d)A}^{\text{HF}}$ are measured at mid-rapidity and integrated over the range $p_T = 1\text{--}3 \text{ GeV}/c$.

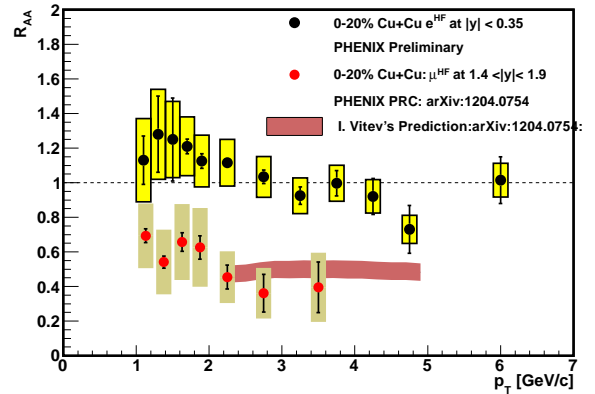


Figure 6. Nuclear modification factor $R_{\text{CuCu}}^{\text{HF}}$ for semileptonic decays of heavy quarks in Cu+Cu collisions at 200 GeV. The data at forward rapidity is compared to the theory curve [7, 17].

Recently, PHENIX has measured new results on open heavy flavor (HF) production in d+Au collisions via semi-leptonic decays at mid-rapidity [2]. The p_T dependence of the nuclear modification is shown in Fig 4 for central and peripheral collisions. Enhancement is observed for the 0-20% most central collisions in the p_T range 1–5 GeV/c, while little or no enhancement is observed for peripheral collisions. At high p_T , where strong suppression is observed for HF

electrons in Au+Au collisions, the measured R_{dAu}^{HF} is consistent with unity. Thus, the suppression observed in Au+Au collisions can be attributed, within the uncertainties on R_{dAu}^{HF} , to hot nuclear matter effects. There are new semi-leptonic decay open heavy flavor PHENIX results for heavy ions that include Cu+Cu R_{AA}^{HF} data at both mid- and forward-rapidity. In Fig. 5, the mid-rapidity Cu+Cu R_{AA}^{HF} data are compared as a function of N_{coll} with data from d+Au and Au+Au collisions. The data are shown for p_T range 1 to 3 GeV/c. Where they overlap, the three data sets are found to display similar behavior with N_{coll} within uncertainties. It is noteworthy that the d+Au data and the peripheral Cu+Cu data have very similar modifications (including some enhancement at $N_{coll} \sim 10$). However, a comparison of forward (muon) and midrapidity (electron) R_{AA}^{HF} in central (0–20%) Cu+Cu collisions shown an unexpected discrepancy [7, 17]. We observe that R_{AA}^{HF} (Cu+Cu) at forward rapidity is suppressed compared to R_{AA}^{HF} (Cu+Cu) at mid-rapidity, suggesting the possibility that cold nuclear matter effects are larger at forward rapidity. The observed suppression is consistent with a calculation [17] that includes the effects of heavy-quark energy loss and in-medium heavy-meson dissociation, as well as cold nuclear matter effects due to shadowing and initial state energy loss due to multiple scattering of incoming partons before they interact to form the $c\bar{c}$ pair.

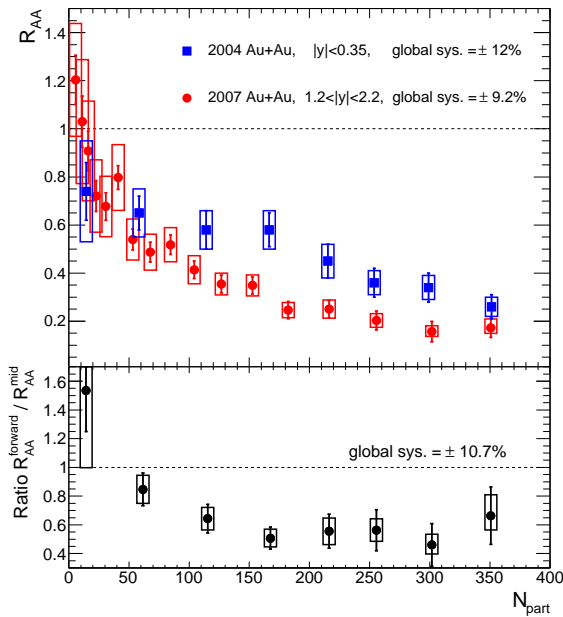


Figure 7. J/ψ R_{AA}^{HF} as a function of N_{part} in Au+Au collisions at 200 GeV. Error bars represent the statistical uncertainties. The boxes represent the point-to-point correlated systematics. The lower panel contains the ratio of forward rapidity to mid-rapidity [20].

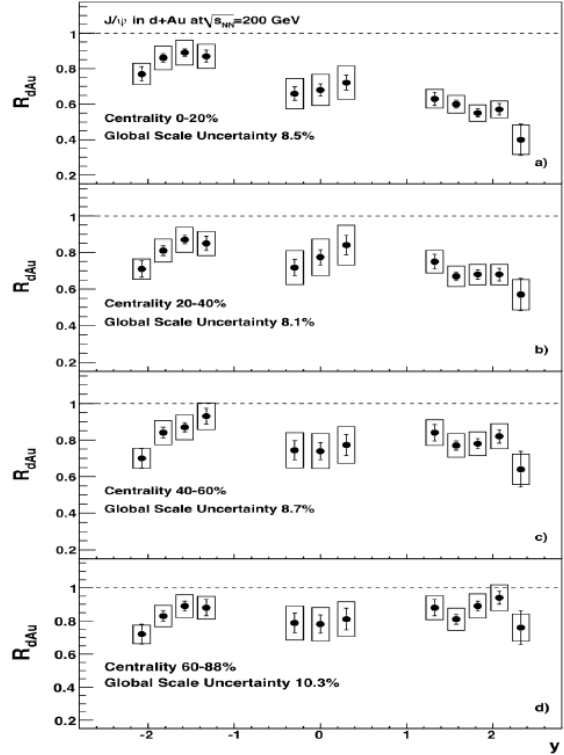


Figure 8. J/ψ R_{dAu}^{HF} versus rapidity for four centrality bins in d+Au collisions at 200 GeV [21].

4. Heavy quarkonia

Heavy quarkonia have long been proposed as a sensitive probe of the color screening length and deconfinement in the quark-gluon plasma [18]. The picture that was originally proposed is complicated by competing effects, which modify quarkonia production and survival in cold and hot nuclear matter. Heavy quarkonia measurements are made in PHENIX either by

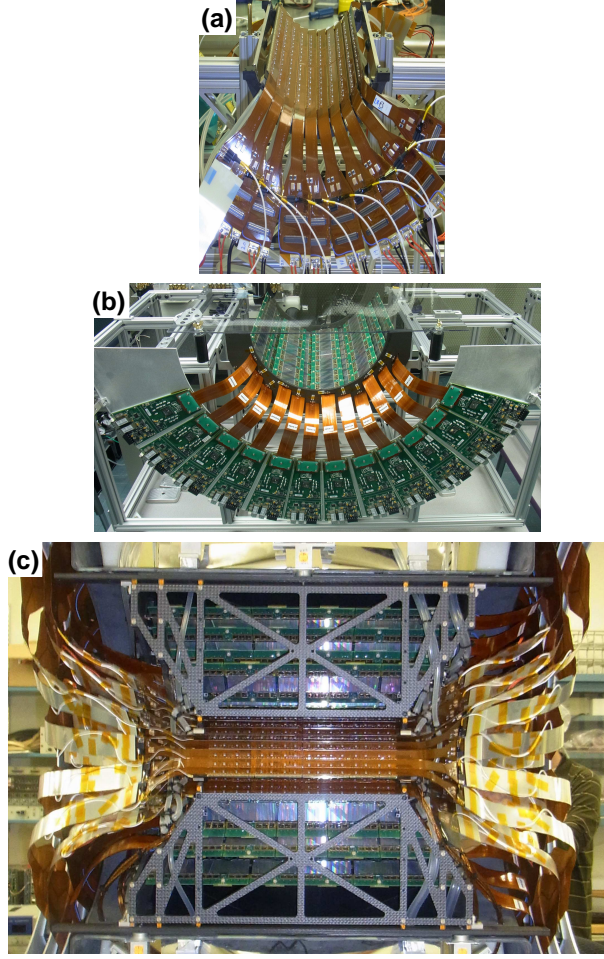


Figure 9. The PHENIX Silicon Vertex Tracker (VTX). Panels (a), (b) are end-views and (c) is a side view. Panels (a) and (b) show the ladders of half barrels of pixel and stripixel detectors, respectively. Panel (c) shows assembled half VTX [22, 23].

detecting opposite sign electrons at mid-rapidity ($|y| < 0.35$) or by detecting opposite sign muons at forward rapidity ($1.2 < |y| < 2.2$), reconstructing the invariant mass of the di-lepton pair, and subtracting the continuum background [19]. The nuclear modification factor, R_{AA} , for J/ψ as a function of centrality (N_{part}) at mid-rapidity and forward rapidity from Au+Au collisions is shown in Fig. 7. The data show that the suppression of J/ψ at forward rapidity is stronger than at mid-rapidity. The comparison of the experimental data to the most recent theoretical calculations that incorporate a variety of physics mechanisms including gluon saturation, gluon shadowing, initial-state parton energy loss, cold nuclear matter breakup, color screening, and charm recombination has been published by PHENIX in Ref. [20]. Figure 8 shows the J/ψ R_{dAu}^{HF} as a function of rapidity for each of the four centrality bins. The forward rapidity data for the most central collisions show a suppression of about 50%. Using these measurements, various models have been suggested to describe the cold nuclear matter effects on J/ψ production used by PHENIX in Ref. [21].

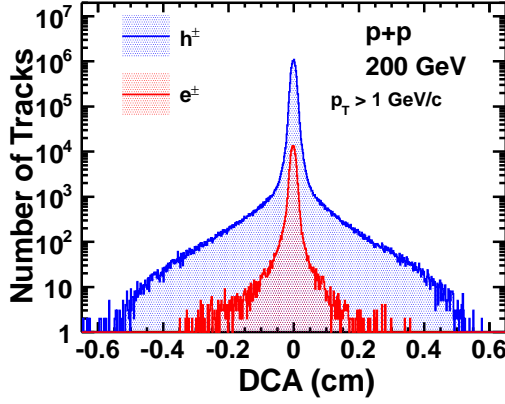


Figure 10. DCA distribution for charged hadrons and electrons (candidates from HF decays) in $p + p$ collisions at 200 GeV. The DCA are integrated for transverse momentum $p_T > 1$ GeV/ c .

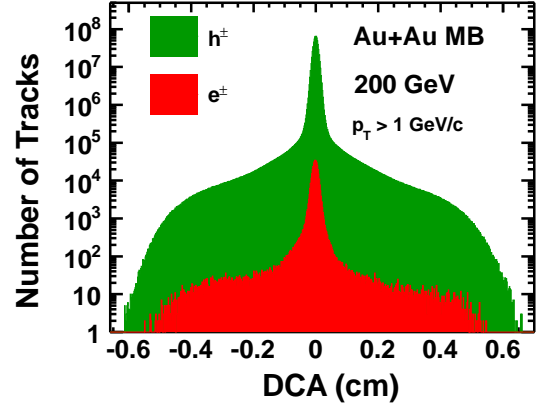


Figure 11. DCA distribution for charged hadrons and electrons (candidates from HF decays) in minimum-bias Au+Au collisions at 200 GeV. The DCA are integrated for transverse momentum range $p_T > 1$ GeV/ c .

5. New era of heavy flavor measurements : PHENIX Silicon Vertex Tracker

For these early results, PHENIX was not able to distinguish electrons coming from the semi-leptonic decay of D and B mesons independently. In order to understand these medium effects in more detail it is imperative to *directly* measure the nuclear modification and the flow of D and B mesons separately. Based on this motivation and impelled by the exciting physics we had already uncovered, in December 2010, the PHENIX Collaboration opened new era for measuring heavy flavor at RHIC by installing new detector called the Silicon Vertex Tracker (VTX) [22, 23]. The VTX was commissioned with $p + p$ at 500 GeV, and took data of $p + p$ and Au+Au during Run-11 and, $p + p$, Cu+Au and U+U during Run-12 at RHIC. The VTX detector consists of four layers of barrel detectors located in the region of pseudorapidity $|\eta| < 1.2$ and covers almost the full azimuth. The two inner barrels of the VTX detector consist of silicon pixel detector. and the two outer barrels of the VTX are constructed using silicon stripixel sensors. Figure 9 shows the ladders of half barrels of pixel and stripixel, as well one complete half of the assembled VTX detector.

The key element needed in directly identifying D and B mesons in PHENIX is the ability to measure the collision vertex position with high accuracy and to compare that with the trajectory for each track. D and B mesons decay into light mesons or leptons before reaching the detectors, thus the daughter particles are observed. As these do not originate at the collision vertex position, a large distance (the decay-length of D^0 and B^0 are 123 and 457 μm , respectively) occurs between the vertex position and the daughter particle trajectory. Based on the VTX detector measurements of the primary vertex, the beam size, and individual tracks for each collision like in Au+Au or in $p + p$ collisions, the reconstructed distance of closest approach (DCA) distribution from primary vertex has been determined. In the present results from $p + p$ collisions at 200 GeV, the DCA distribution was obtained using beam center (instead primary vertex) to avoid auto-correlation (in $p + p$ there are only few tracks). DCA distributions in $p + p$ and Au+Au collisions at 200 GeV obtained from RHIC Run-11 and Run-12 are presented in Fig. 10 and Fig. 11, respectively. Figure 11 shows that the DCA resolution of individual tracks to the primary vertex, $\sigma(\text{DCA})$, is about 70 μm . The achieved DCA resolution is sufficient to

distinguish D - and B -mesons from the difference of their decay-length. These measurements using PHENIX VTX detector clearly illustrate that this detector is working as expected and future heavy flavor physics program in PHENIX is very promising.

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